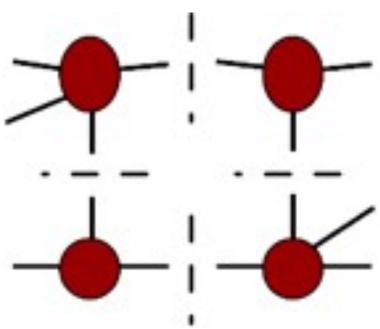
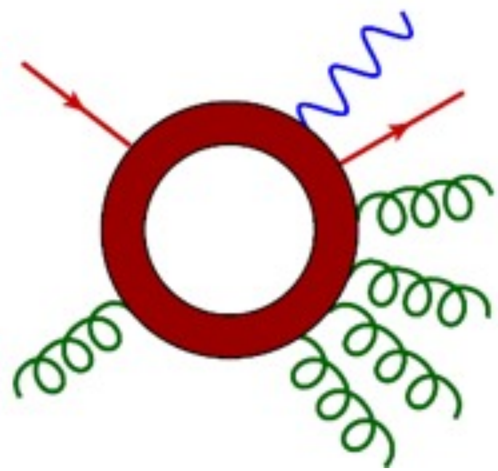
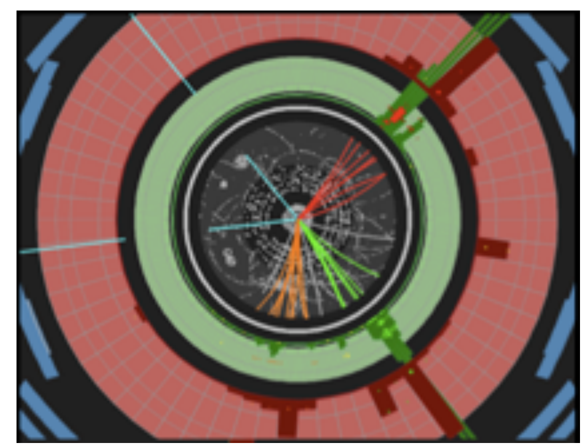
The recent revolution in NLO QCD predictions for the LHC







Lance Dixon

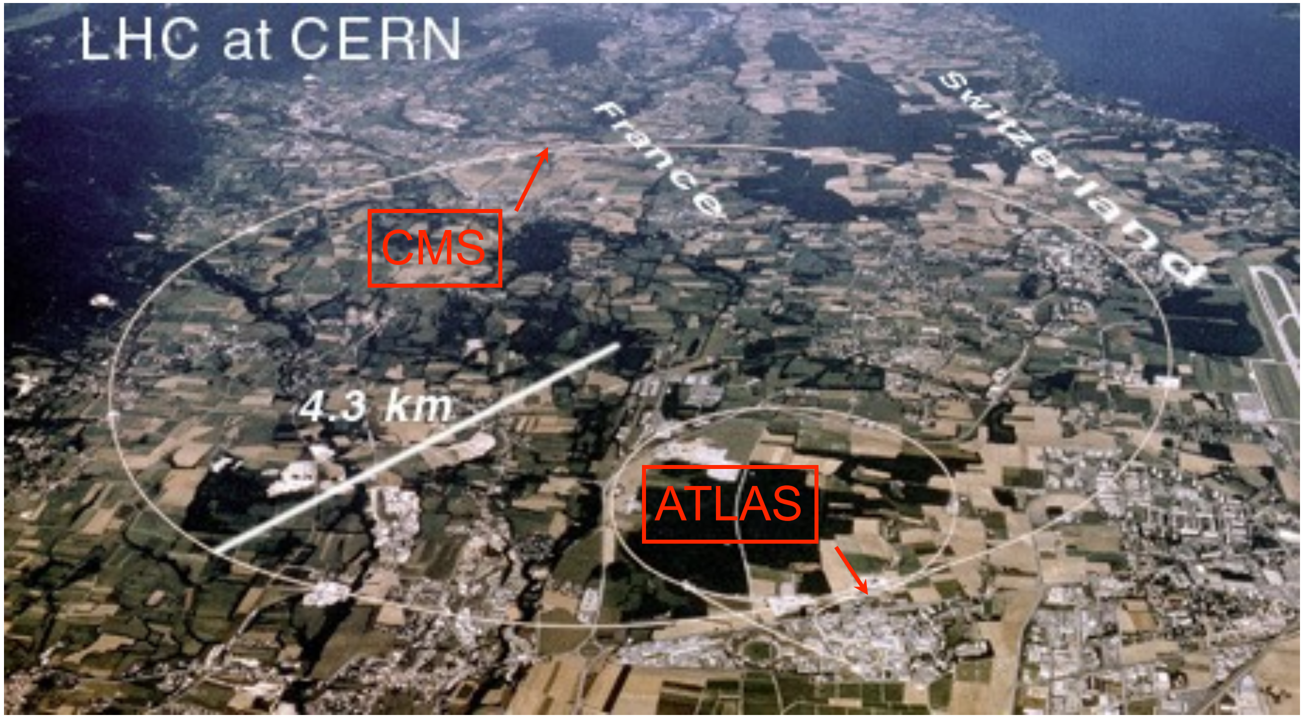
LBL Research Progress Meeting

February 16 2012

SLAC
NATIONAL ACCELERATOR LABORATORY

"New physics at the LHC is a riddle, wrapped in a mystery, inside an enigma; but perhaps there is a key." -W. Churchill

The Large Hadron Collider



- Proton-proton collisions at **7 → 14 TeV** center-of-mass energy, 3.5 → 7 times greater than previous (Tevatron)
- Luminosity (collision rate) 10-100 times greater

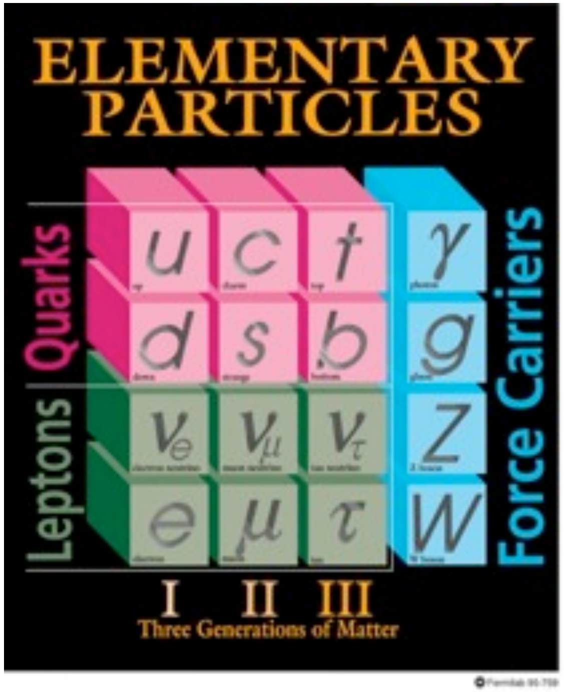
Brand new window into physics at shortest distance scales

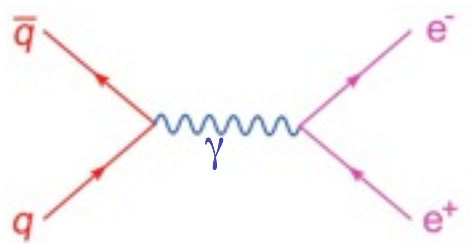
Standard Model

- All elementary forces except gravity in same basic framework
- Matter made of spin ½ fermions
- Forces carried by spin 1 vector bosons: γ $W^+ \, W^- \, Z^0$ g
- Add a spin 0 Higgs boson H to explain masses of $W^+ \, W^- \, Z^0$

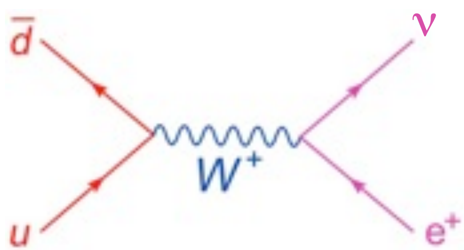
(plus all elementary fermions)

→ finite, testable predictions for all quantities

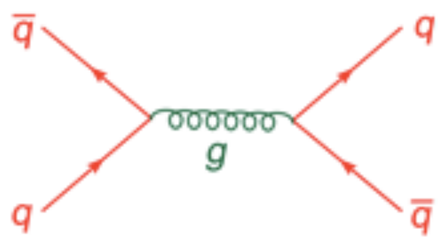




electromagnetism (QED)



weak



strong (QCD)

New Physics at LHC

LHC built to explore new physics at 100 GeV – 1 TeV mass scale associated with weak boson masses.
At very least, should be a Higgs boson (or similar)

Many theories predict host of new massive particles, often including a **dark matter candidate (WIMP)**

- **supersymmetry**
- **new dimensions of space-time**
- **new forces**
- etc.

- Most new massive particles decay rapidly to old, ~massless particles: quarks, gluons, charged leptons, neutrinos, photons

- **How to distinguish new physics from old (Standard Model)?**
- **From other types of new physics?**

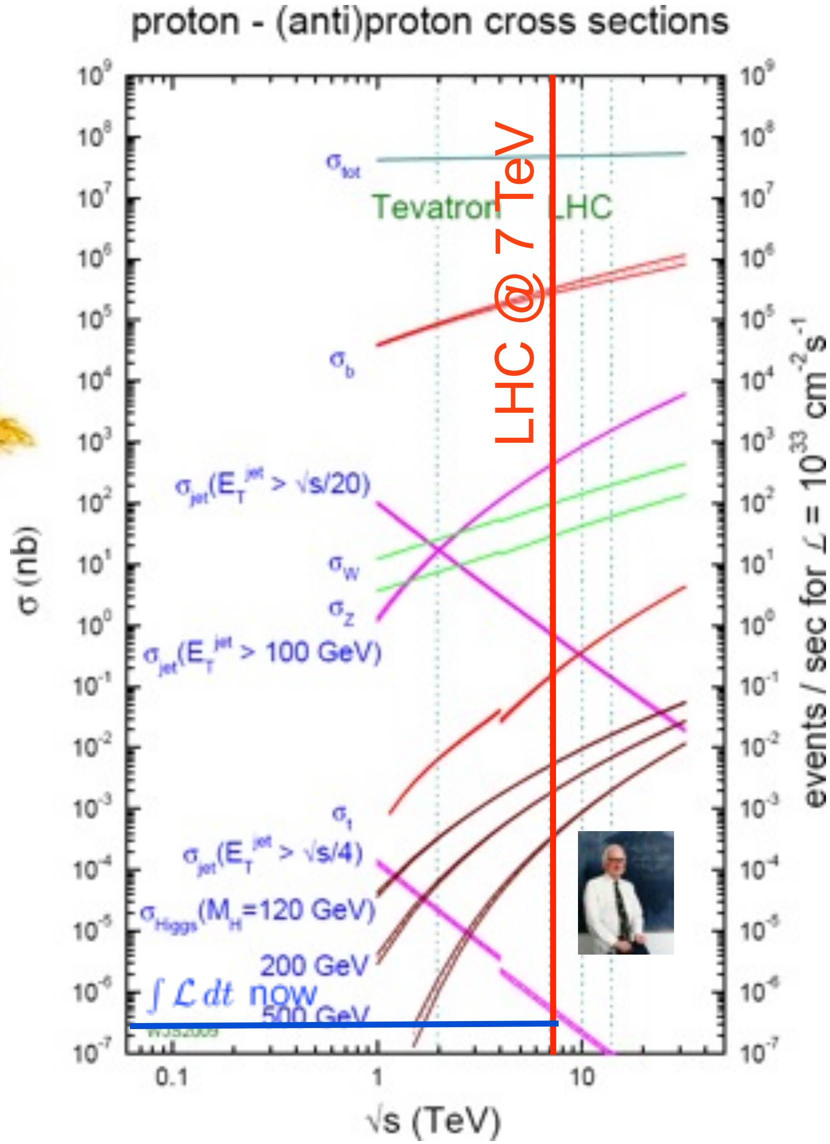
Signals vs. Backgrounds

vs.

electron-positron colliders
– small backgrounds

hadron colliders
– large backgrounds

LHC Data Dominated by Jets



Jets from quarks and gluons.

- *q,g* from decay of new particles?
- Or from old QCD?

- Every process shown also with one more jet at ~ 1/5 the rate
- Need **accurate production rates** for

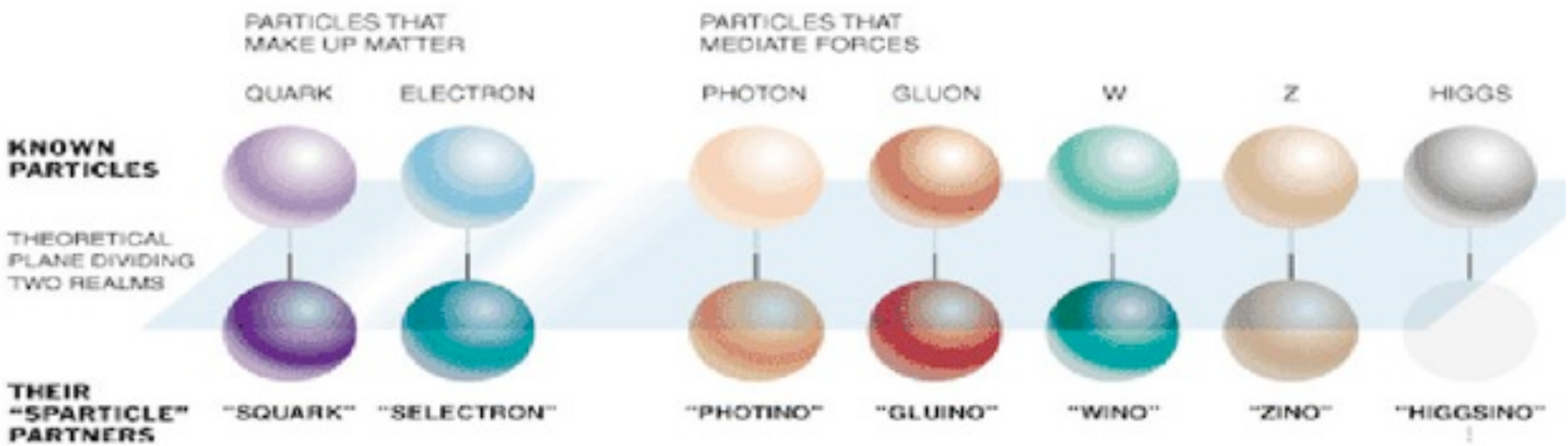
X + 1,2,3,… jets

in Standard Model

new physics

Supersymmetry

• Relates particles with integer spin (bosons) to particles with ½ integer spin (fermions)
• Phenomenological version ($\mathcal{N} = 1$ supersymmetry) predicts a host of new particles to be discovered soon at the LHC

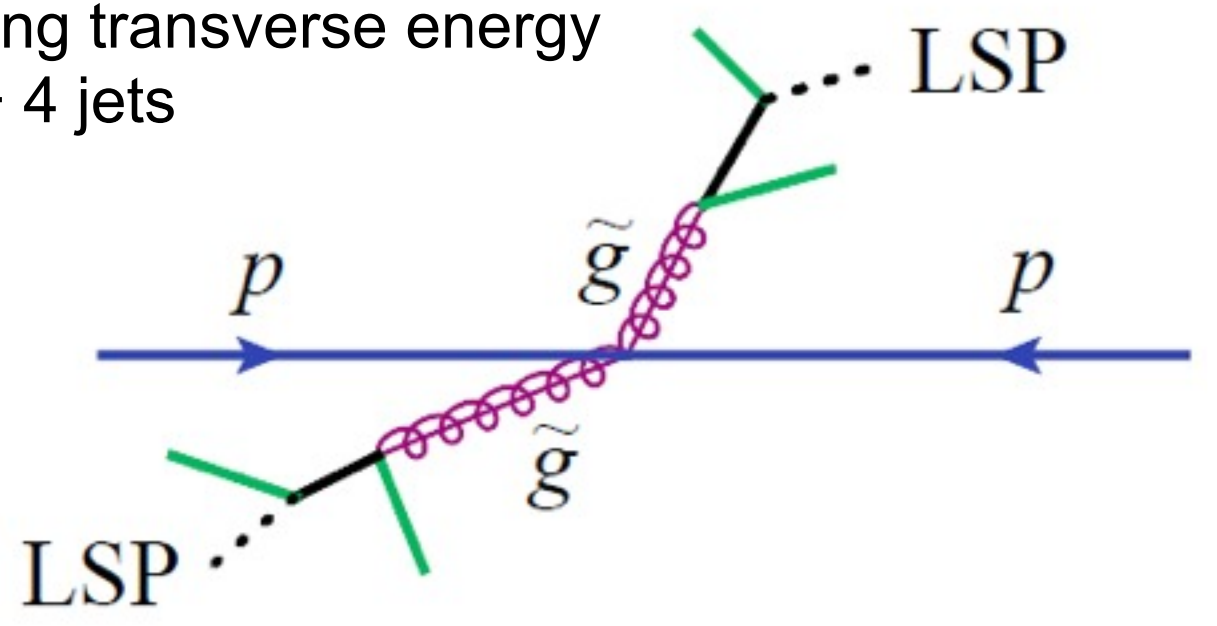


• Supersymmetry is just one possible type of new physics
• Even within supersymmetry, many different possible signatures
• Need precise predictions for many different background processes (Higgs also needs precision predictions, but somewhat different…)

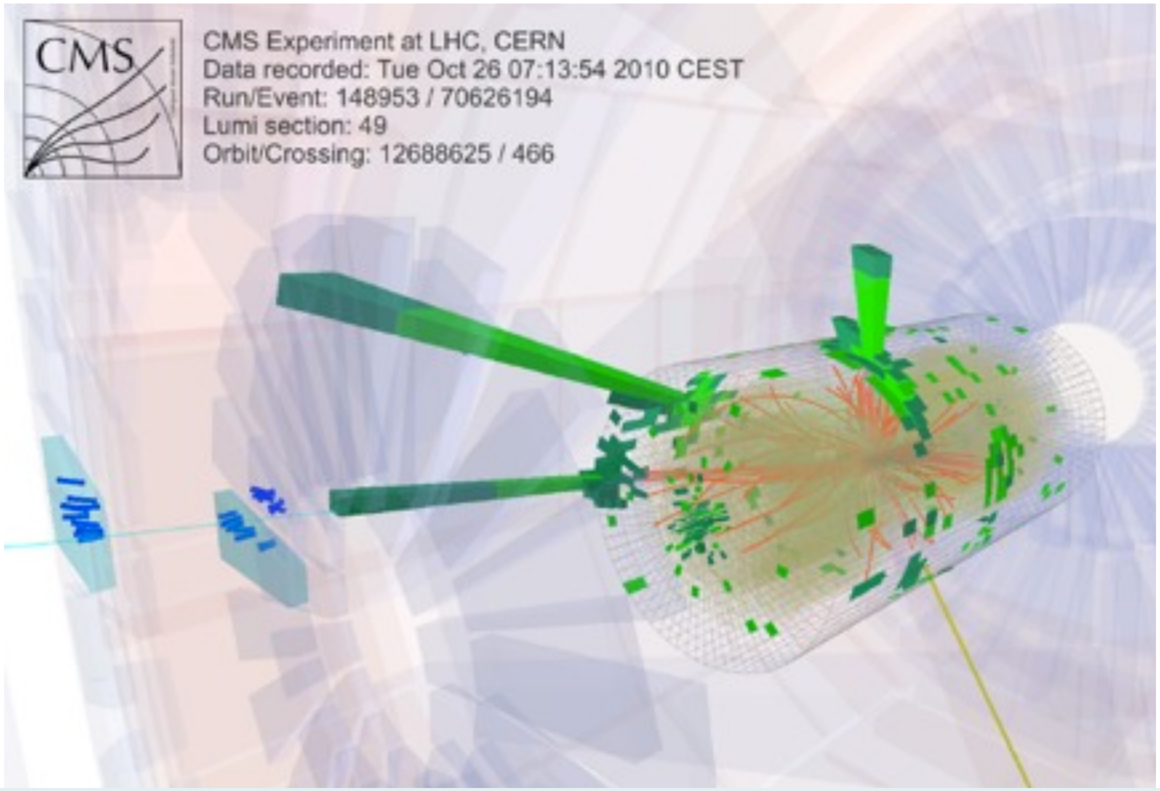
Classic SUSY dark matter signature

In models such as supersymmetry, heavy produced particles (colored) decay rapidly to stable Weakly Interacting Massive Particle (WIMP) plus jets

→ Missing transverse energy
MET + 4 jets



Is LHC already making dark matter?



- 5 jets
- sum of jet transverse momenta H_T= 1132 GeV
- missing transverse energy H_{TMiss} = 693 GeV

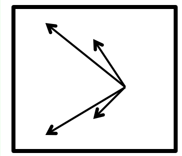
But it happens in Standard Model too

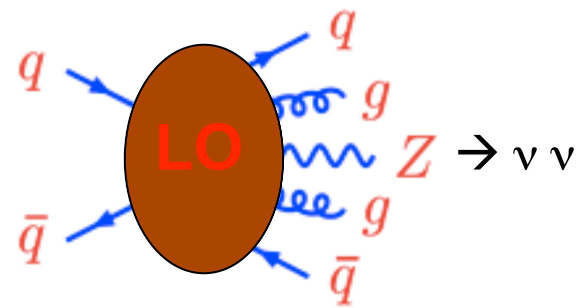
- **MET + 4 jets from**

  pp → Z + 4 jets,

  Z → neutrinos

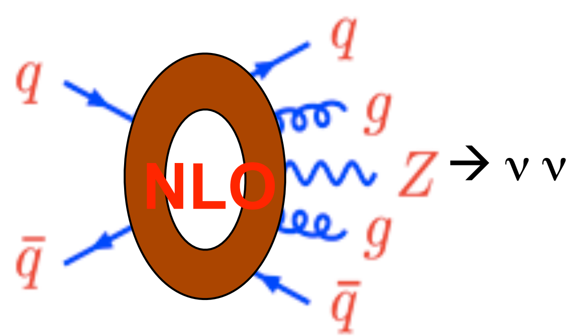
Neutrinos also weakly interacting, escape detector.
Irreducible background.





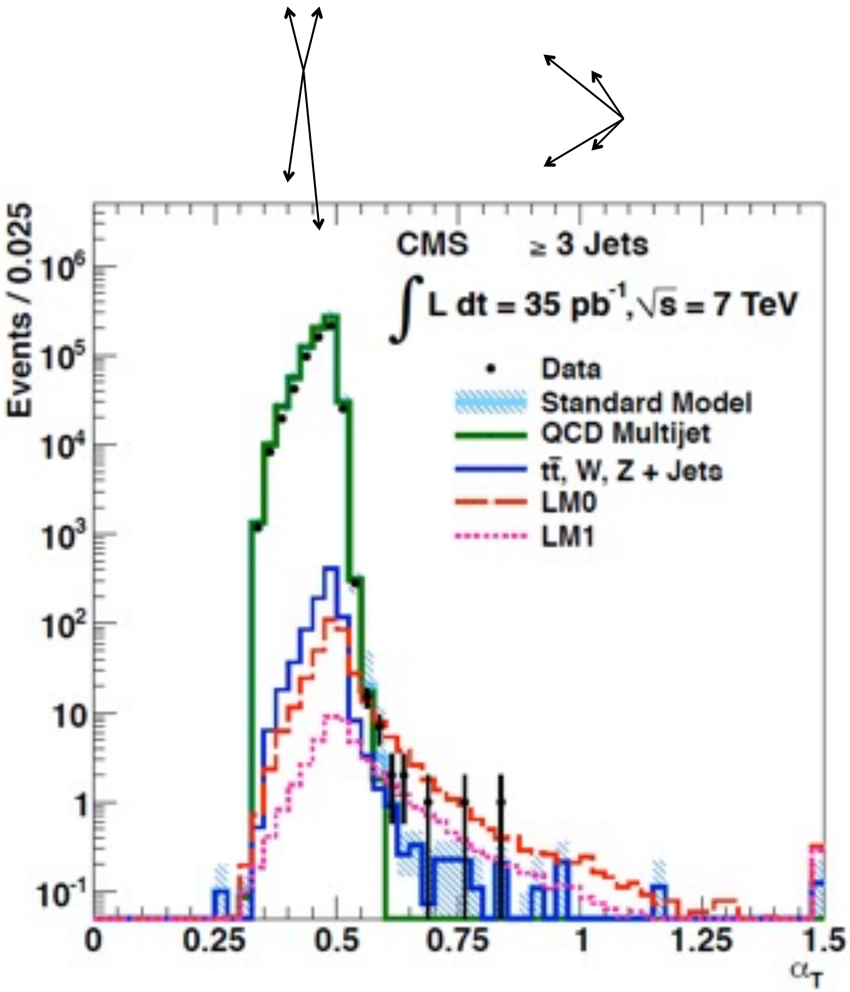
Until very recently, state of art for Z + 4 jets based on **Leading Order (LO) approximation in QCD**
→ **normalization uncertain**

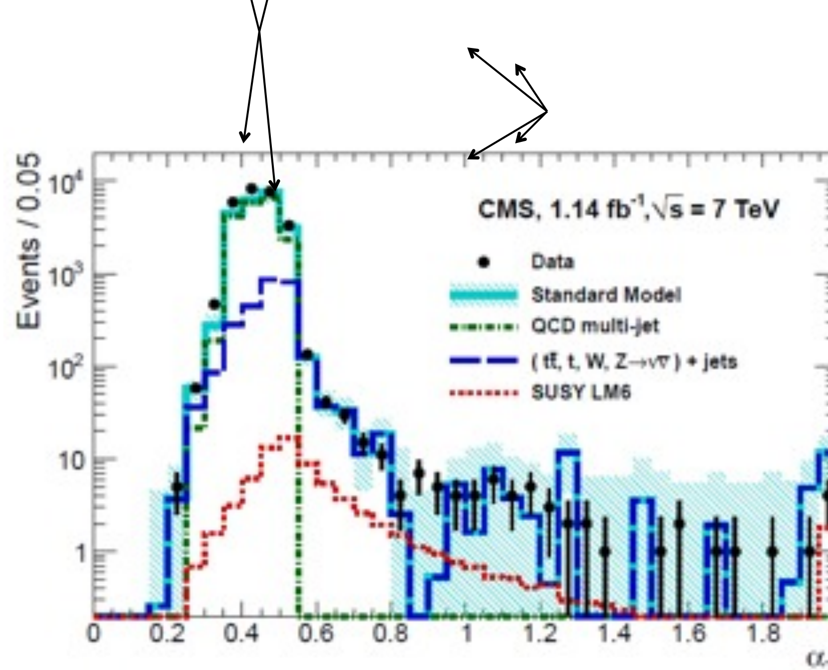
Now available at **Next to Leading Order**, greatly reducing theoretical uncertainties

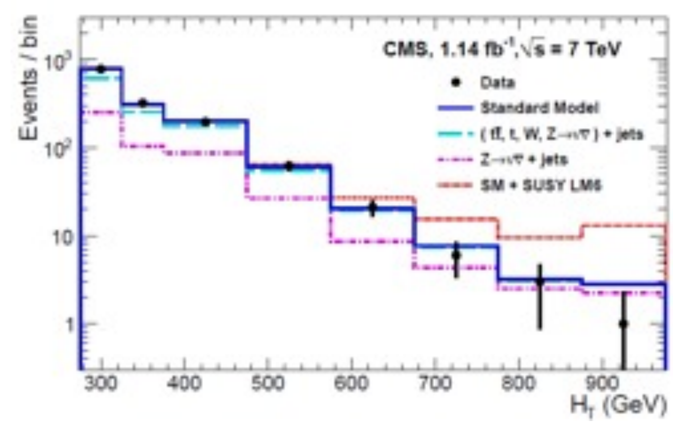


MET + jets search at CMS

1101.1628, 1109.2352







α_T ~ misalignment of MET with main jet axis

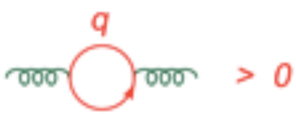
The NLO revolution

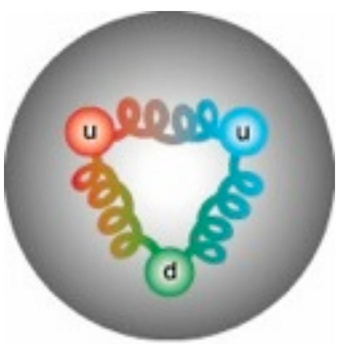
- Many important hadron collider processes have been computed at NLO in the past three years, beyond what was previously thought possible
- Required a new understanding of scattering amplitudes, at a formal level, as well as efficient, stable implementation
- Many people contributed to this progress
- The revolution is far from over

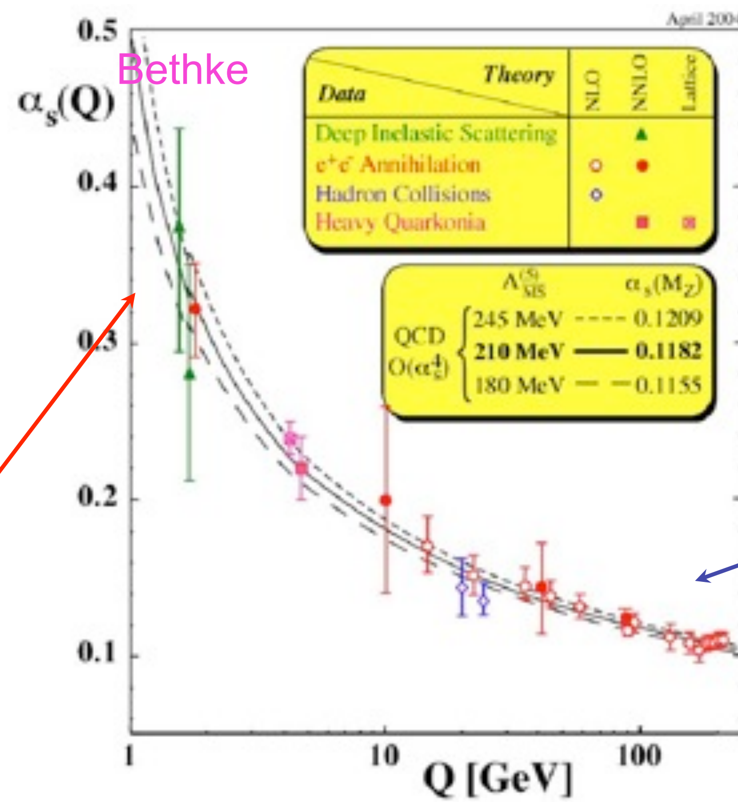
QCD Asymptotically Free

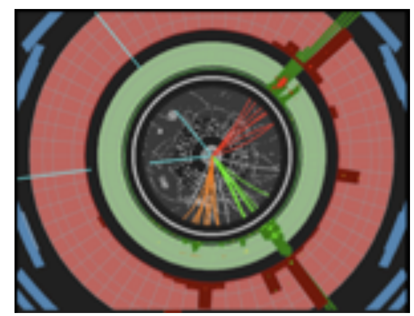
gluons anti-screen charge → α_s small, **QCD calculable** at short distances

Gross, Wilczek, Politzer (1973)



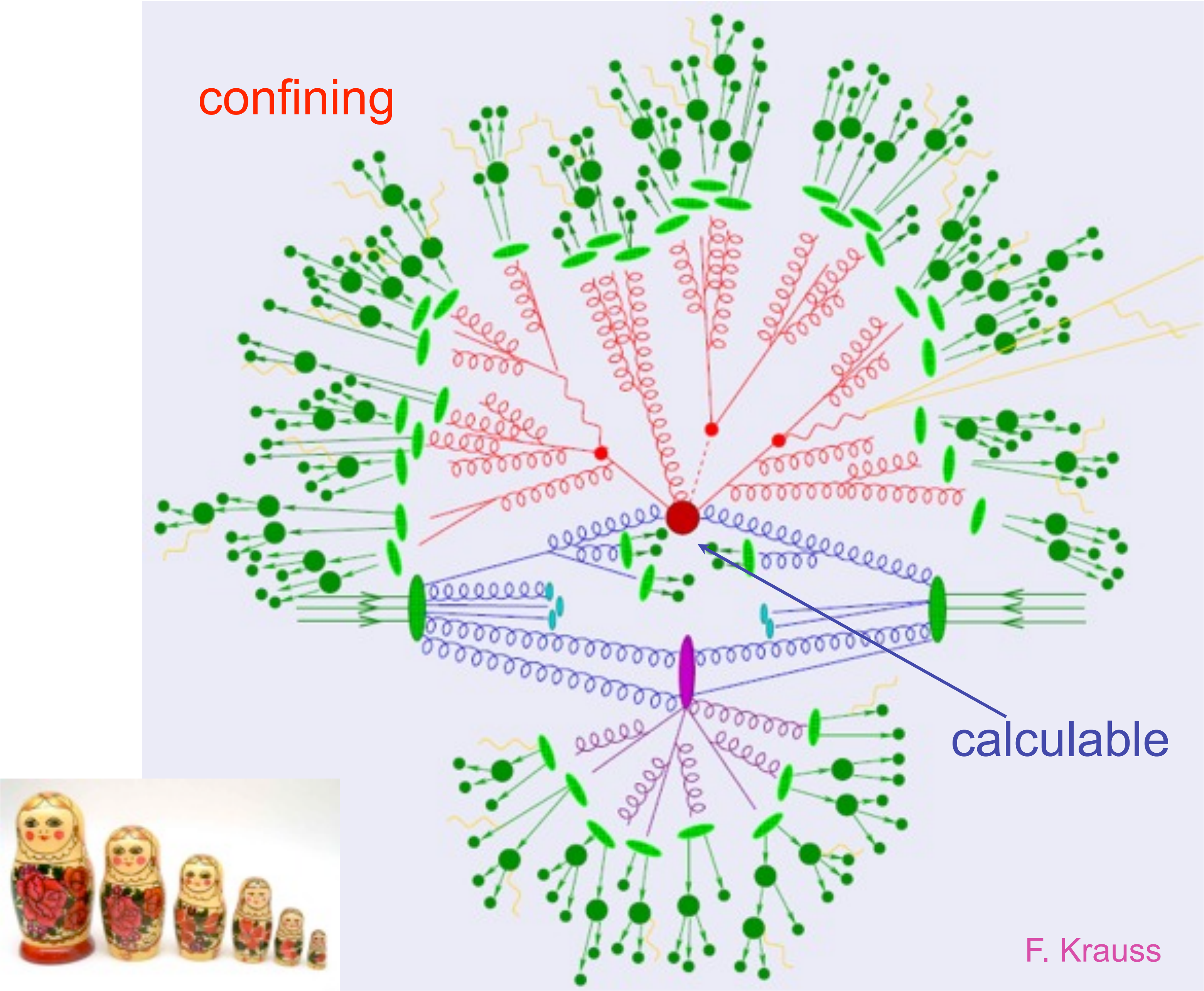






calculable

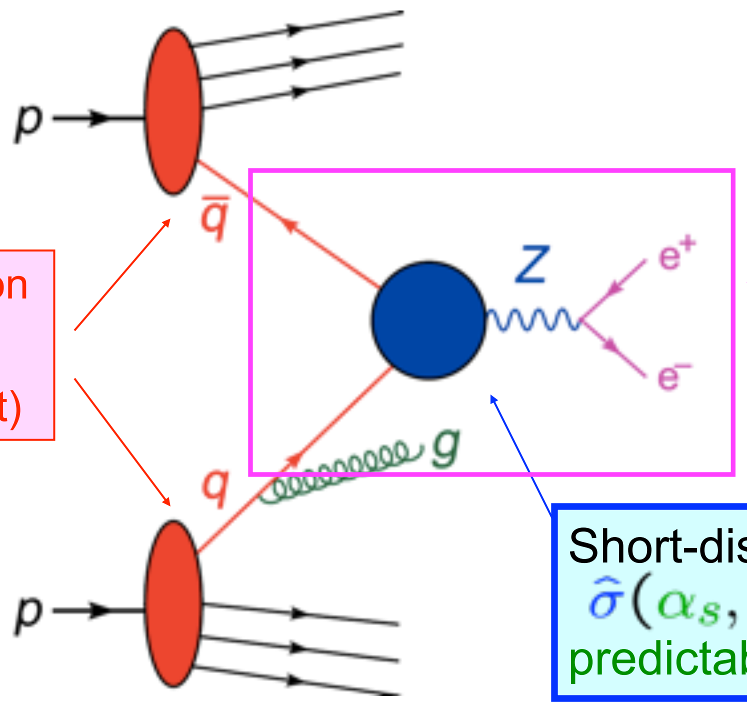
confining


confining
calculable
F. Krauss

QCD Factorization & Parton Model

Quarks and gluons (partons) in proton almost free, sampled one at a time in hard collisions

Parton distribution functions (from experiment)



Box separates “femto-universe” from long-distance effects like parton distributions.

size = factorization scale μ_F (“arbitrary”)

Short-distance cross section $\hat{\sigma}(\alpha_s, \mu_F, \mu_R)$ predictable using perturbative QCD

Renorm. scale (“arbitrary”)

Short-Distance Cross Section in Perturbative QCD

$$\hat{\sigma}(\alpha_s,\mu_F,\mu_R) \;=\; [\alpha_s(\mu_R)]^{n_\alpha}\left[\hat{\sigma}^{(0)} + \frac{\alpha_s}{2\pi}\hat{\sigma}^{(1)}(\mu_F,\mu_R) + \left(\frac{\alpha_s}{2\pi}\right)^2 \hat{\sigma}^{(2)}(\mu_F,\mu_R) + \cdots\right]$$

LO NLO NNLO

Leading-order (LO) predictions only qualitative:

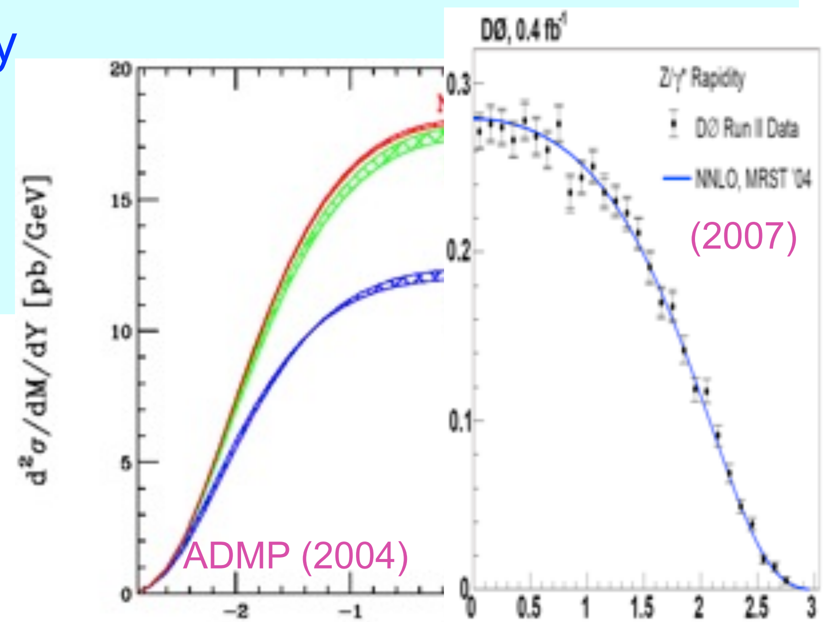
Expansion in $\alpha_s(\mu)$ behaves poorly

- Estimate "error" bands by varying

$$\mu_R = \mu_F = \mu$$

Example: *Z* production at Tevatron as function of rapidity Y (~polar angle)

50% shift, LO → NLO

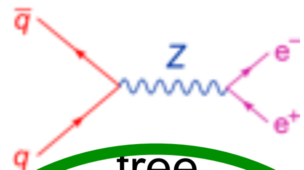


by NNLO, a precision observable

QCD corrections in a nut-shell

"Trivial" example: *Z* production at hadron colliders

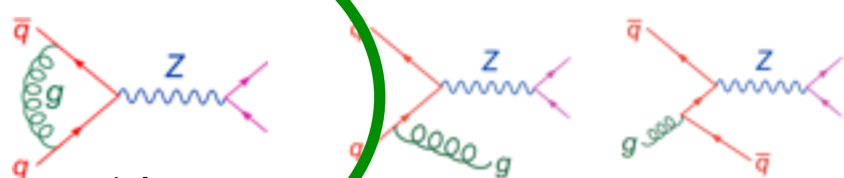
LO $\hat{\sigma}^{(0)}$



tree

was the NLO bottleneck

NLO $\hat{\sigma}^{(1)}$



1 loop

tree + 1 parton

dim. reg. $D = 4 - 2\epsilon$

first, cancel infrared divergences ($1/\epsilon^2$) between virtual & real

NNLO $\hat{\sigma}^{(2)}$

2 loops

1 loop + 1 parton

tree + 2 partons

current NNLO bottleneck

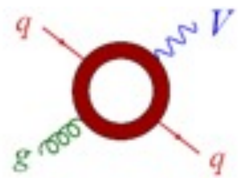
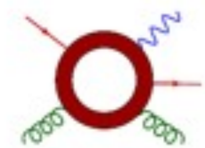
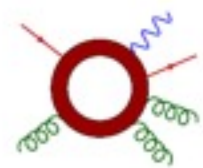
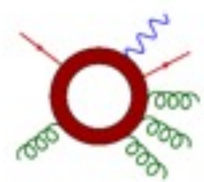
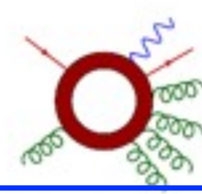
intricate ($1/\epsilon^4$) IR cancellations

Beyond Feynman Diagrams

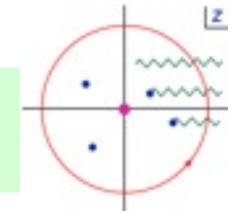
- **Feynman diagrams** are very general and **powerful**
- However, for many applications, **on-shell methods** based on analyticity are a much more efficient way to get the same answer.
- They also give new insight into structure and properties of scattering amplitudes, not only in QCD

Just one QCD loop can be a challenge

$pp \rightarrow$ $W + n$ jets (just amplitudes with most gluons)

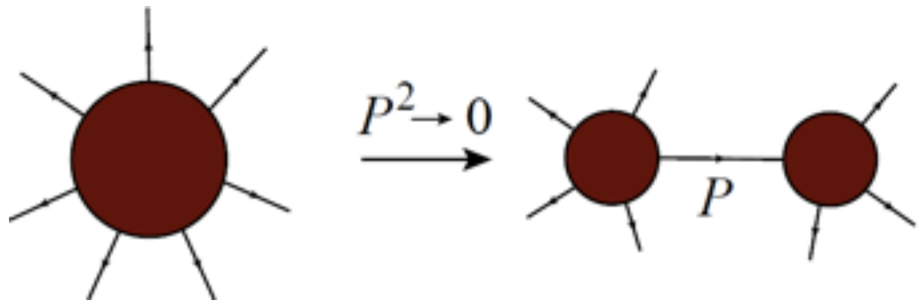
# of jets		# 1-loop Feynman diagrams	
1		11	
2		110	Current limit with Feynman diagrams
3		1,253	
4		16,648	
5		256,265	Current limit with on-shell methods

The Analytic *S*-Matrix



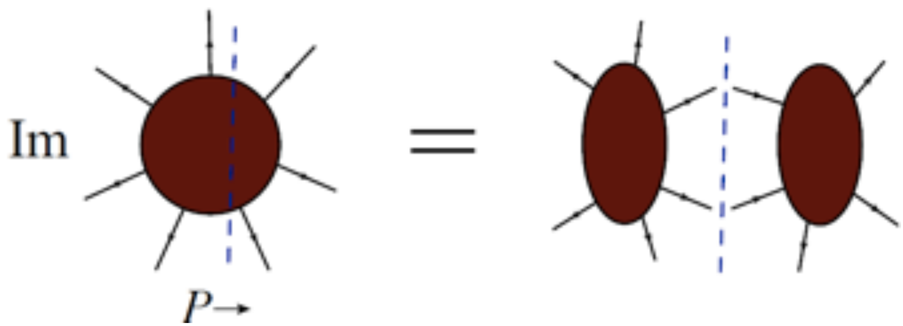
Bootstrap program for strong interactions: Reconstruct scattering amplitudes **directly** from **analytic properties: "on-shell" information**

- Poles



Landau; Cutkosky; Chew, Mandelstam; Eden, Landshoff, Olive, Polkinghorne; Veneziano; Virasoro, Shapiro; … (1960s)

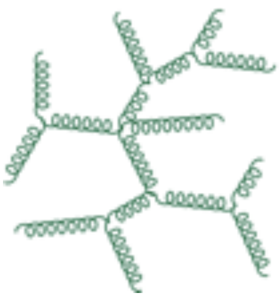
- Branch cuts



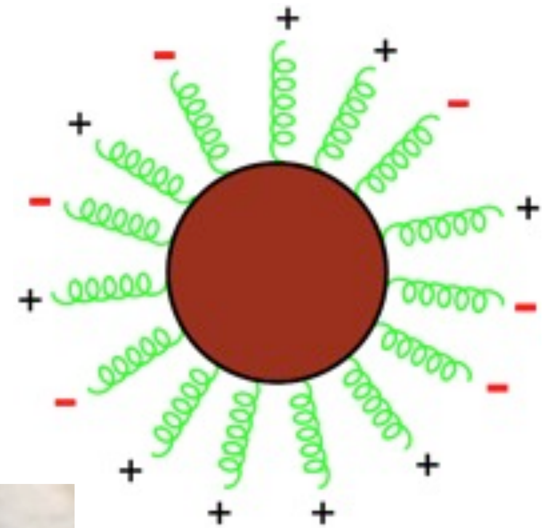
Analyticity fell out of favor in 1970s with the rise of QCD & Feynman rules

Now **resurrected** for computing loop amplitudes in **perturbative QCD** as **alternative to Feynman diagrams! Perturbative information now assists analyticity. Works for many other theories too.**

Granularity vs. Plasticity

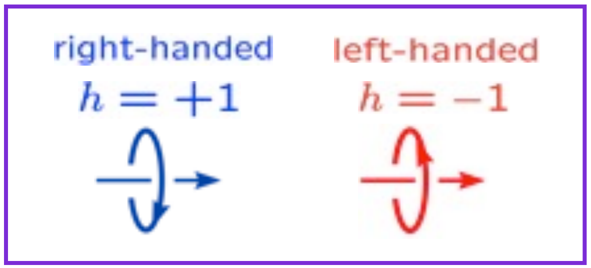


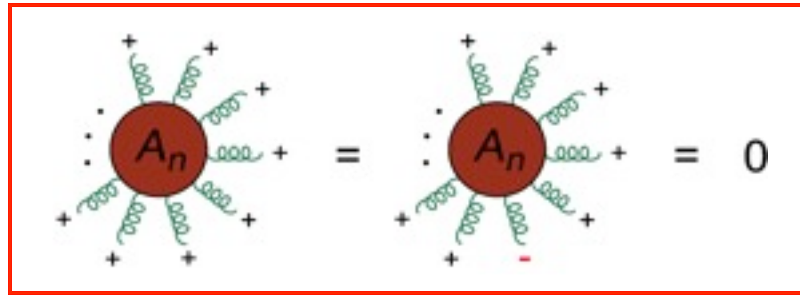
+ ...

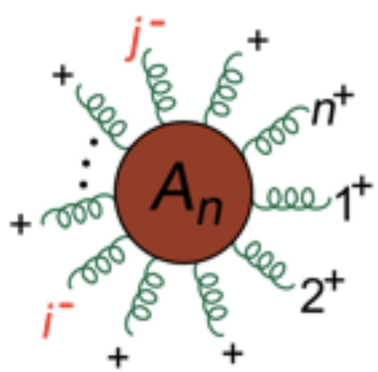


Tree-Level Simplicity

Very simple tree-level helicity amplitudes for QCD, found first in 1980's







$$= \frac{\langle i\, j \rangle^4}{\langle 1\, 2\rangle \langle 2\, 3\rangle \cdots \langle n\, 1\rangle}$$

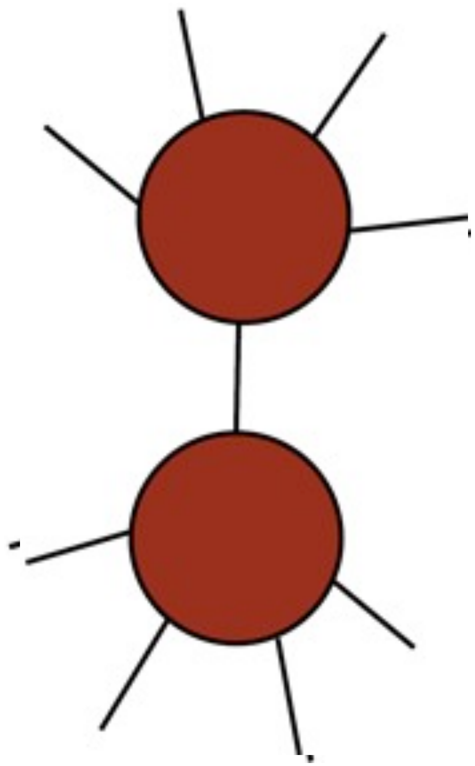
Parke-Taylor formula (1986)

Simplicity very mysterious using Feynman diagrams
(a secret supersymmetry accounts for it)

Want to exploit the simplicity at loop level

Recycling “Plastic” Amplitudes

Amplitudes fall apart into simpler ones in special limits – pole information



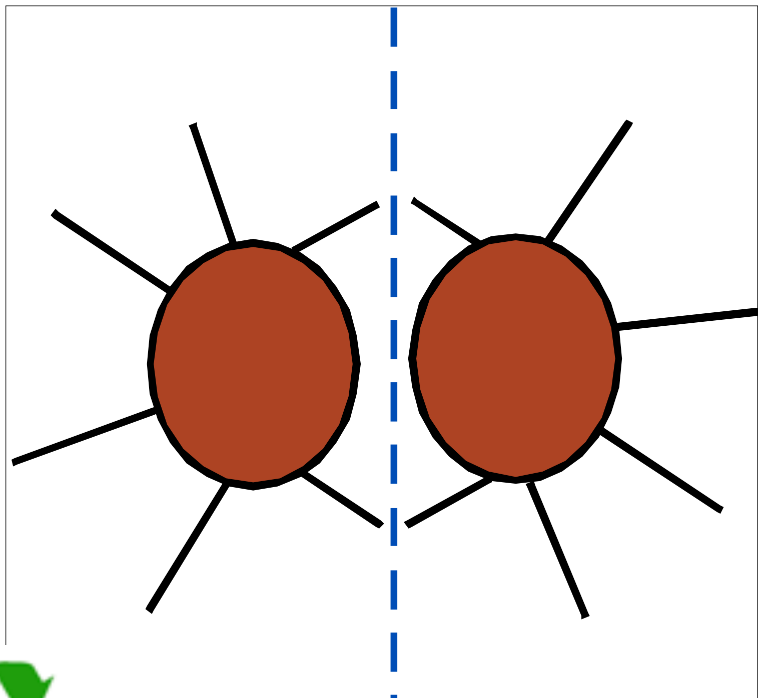
Trees recycled into trees

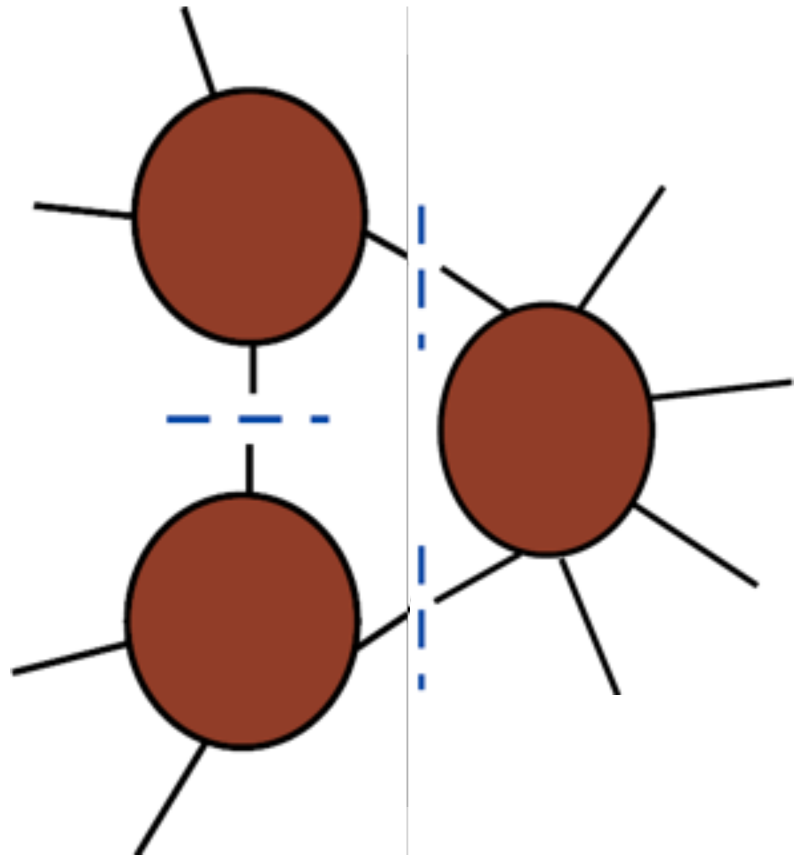
BCFW recursion relations

Generalized Unitarity (One-loop Plasticity)

Ordinary unitarity:
put 2 particles on shell

Generalized unitarity:
put 3 or 4 particles on shell





Trees recycled into loops!

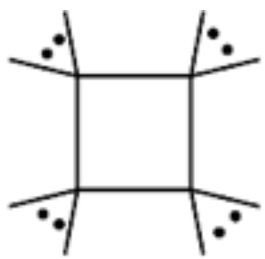
One-loop amplitudes reduced to trees

When all external momenta are in $D = 4$, loop momenta in $D = 4\text{-}2\varepsilon$ (dimensional regularization), one can write:

Bern, LD, Dunbar, Kosower (1994)

coefficients are all rational functions – determine algebraically from products of trees using (generalized) unitarity

$$A^{1\text{-loop}} = \sum_i d_i$$



$$+ \sum_i c_i$$

$$+ \sum_i b_i$$

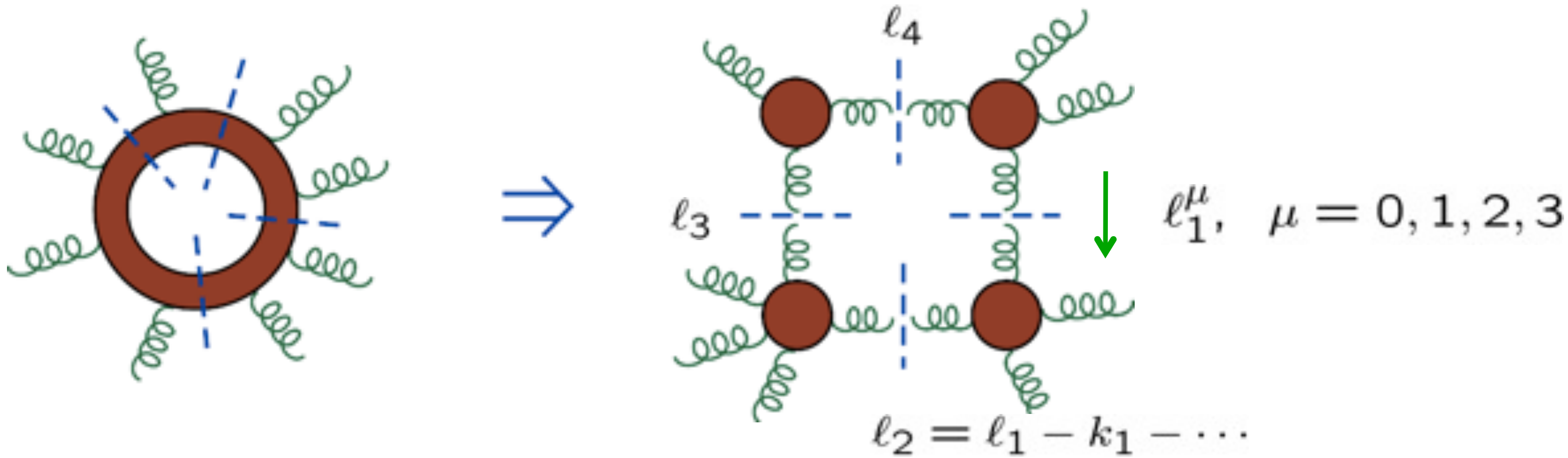
$$+ R + \mathcal{O}(\epsilon)$$

rational part

known **scalar** one-loop integrals, same for all amplitudes

Generalized Unitarity for Box Coefficients d_i

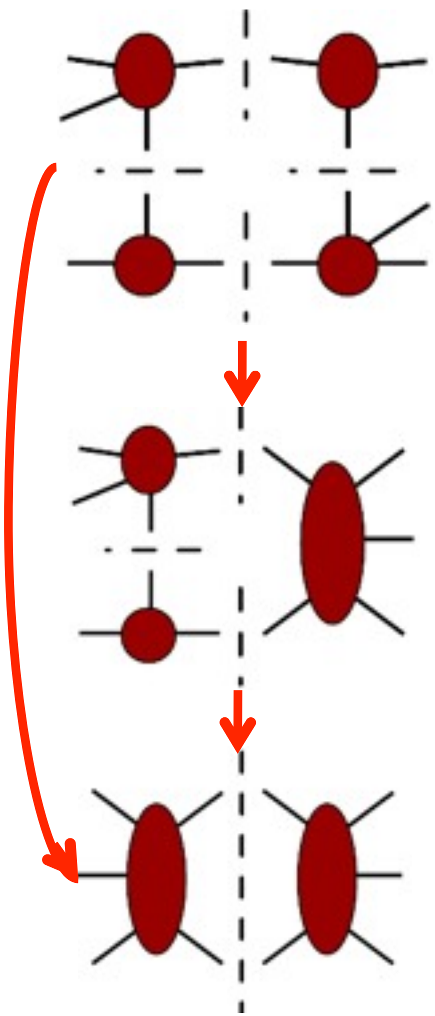
Britto, Cachazo, Feng, hep-th/0412103



Just multiply together 4 different tree amplitudes, evaluated at 2 different loop momenta that solve the 4 "quadruple cut" equations:

$$\ell_1^2 = \ell_2^2 = \ell_3^2 = \ell_4^2 = 0$$

Full amplitude determined hierarchically



Each box coefficient comes unique from 1 "quadruple cut"

Britto, Cachazo, Feng, hep-th/0412103

Ossola, Papadopolous, Pittau, hep-ph/0609007;
Mastrolia, hep-th/0611091; Forde, 0704.1835;
Ellis, Giele, Kunszt, 0708.2398; Berger et al., 0803.4180;…

Each triangle coefficient from 1 triple cut, but "contaminated" by boxes

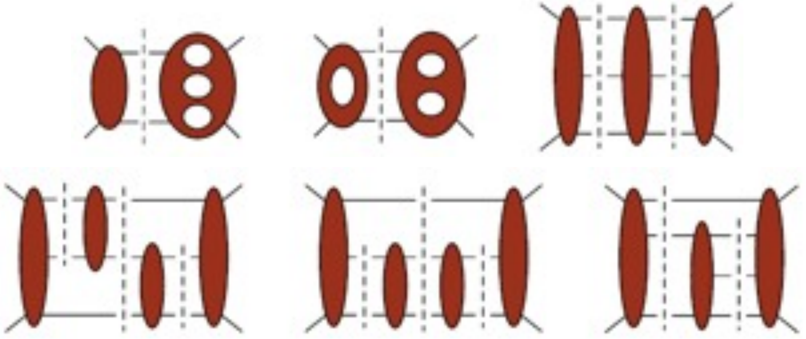
Each bubble coefficient from 1 double cut, removing contamination by boxes and triangles

Rational part depends on all of above

Recycling trees into loops

Also works for multi loop amplitudes

Multi-loop case well-studied in "toy" theory (N=4 super-Yang-Mills)



Multi-loop methods still in infancy for QCD

Bern, LD, De Freitas (2001-2) ; Mastrolia, Ossola, 1107.6041;
Kosower, Larsen, 1108.1180; Badger, Frellesvig, Zhang, 1202.2019

Some Automated On-Shell One Loop Programs

Blackhat: Berger, Bern, LD, Diana, Febres Cordero, Forde, Gleisberg, Höche, Ita, Kosower, Maître, Ozeren, 0803.4180, 0808.0941, 0907.1984, 1004.1659, 1009.2338…
+ Sherpa → NLO W,Z + 3,4,5 jets pure QCD 4 jets

CutTools: Ossola, Papadopolous, Pittau, 0711.3596
NLO WWW, WWZ, ... Binoth+OPP, 0804.0350
NLO $t\bar{t}b\bar{b}$, $t\bar{t}$ + 2 jets,…
Bevilacqua, Czakon, Papadopoulos, Pittau, Worek, 0907.4723; 1002.4009
MadLoop: Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau 1103.0621
HELAC-NLO: Bevilacqua et al, 1110.1499

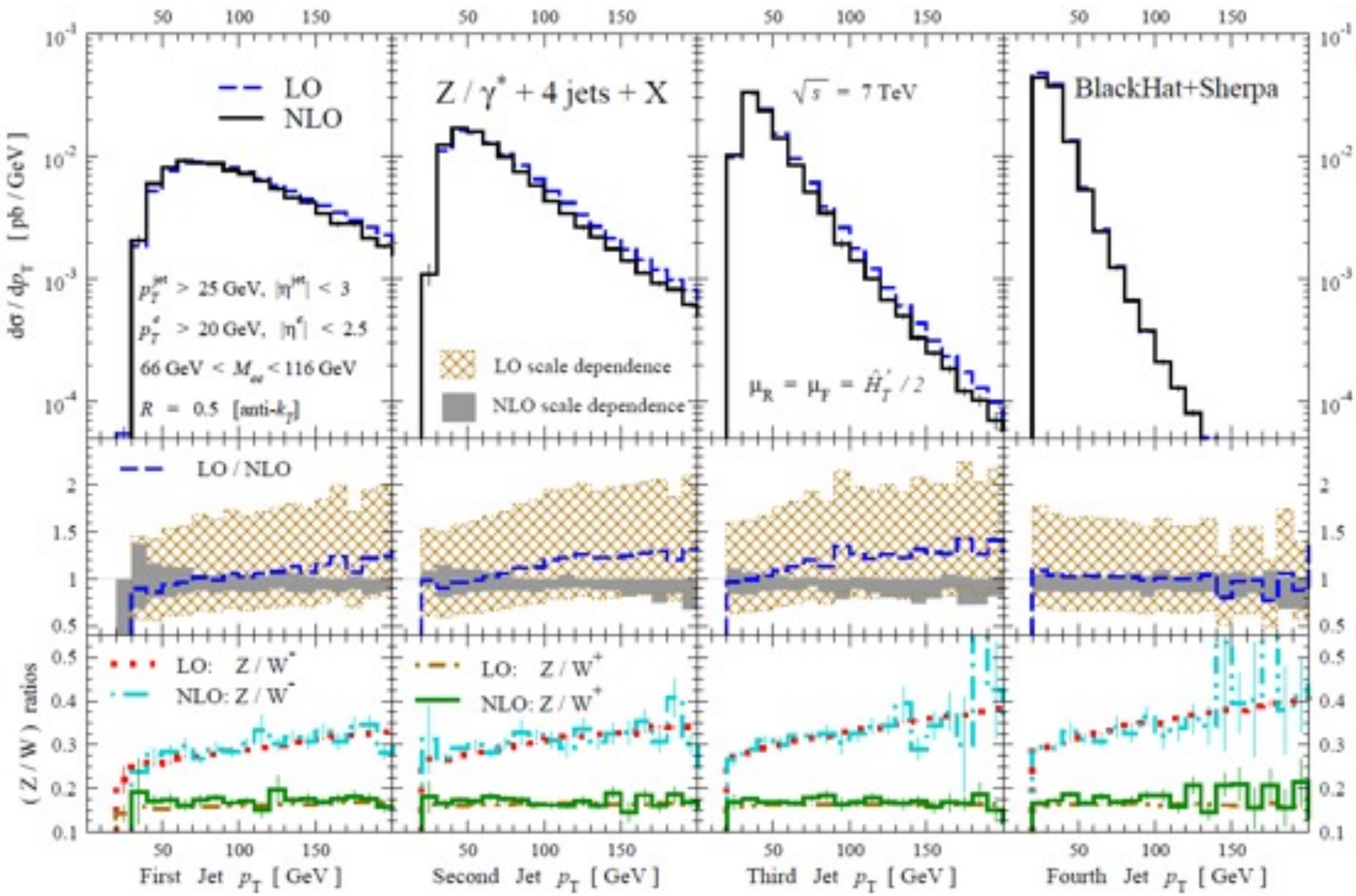
Rocket: Giele, Zanderighi, 0805.2152
Ellis, Giele, Kunszt, Melnikov, Zanderighi, 0810.2762
NLO W + 3 jets Ellis, Melnikov, Zanderighi, 0901.4101, 0906.1445
$W^+W^\pm$ + 2 jets Melia, Melnikov, Rontsch, Zanderighi, 1007.5313, 1104.2327

SAMURAI: Mastrolia, Ossola, Reiter, Tramontano, 1006.0710

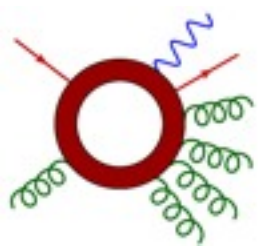
NGluon: Badger, Biedermann, Uwer, 1011.2900

NLO $pp \rightarrow Z + 4$ jets, and ratio to $W^{\pm}$

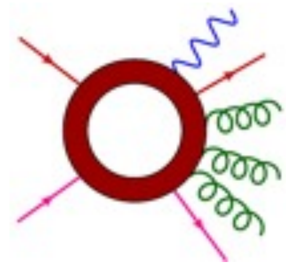
Ita et al. 1108.2229



NLO $pp \rightarrow W + 5$ jets also feasible

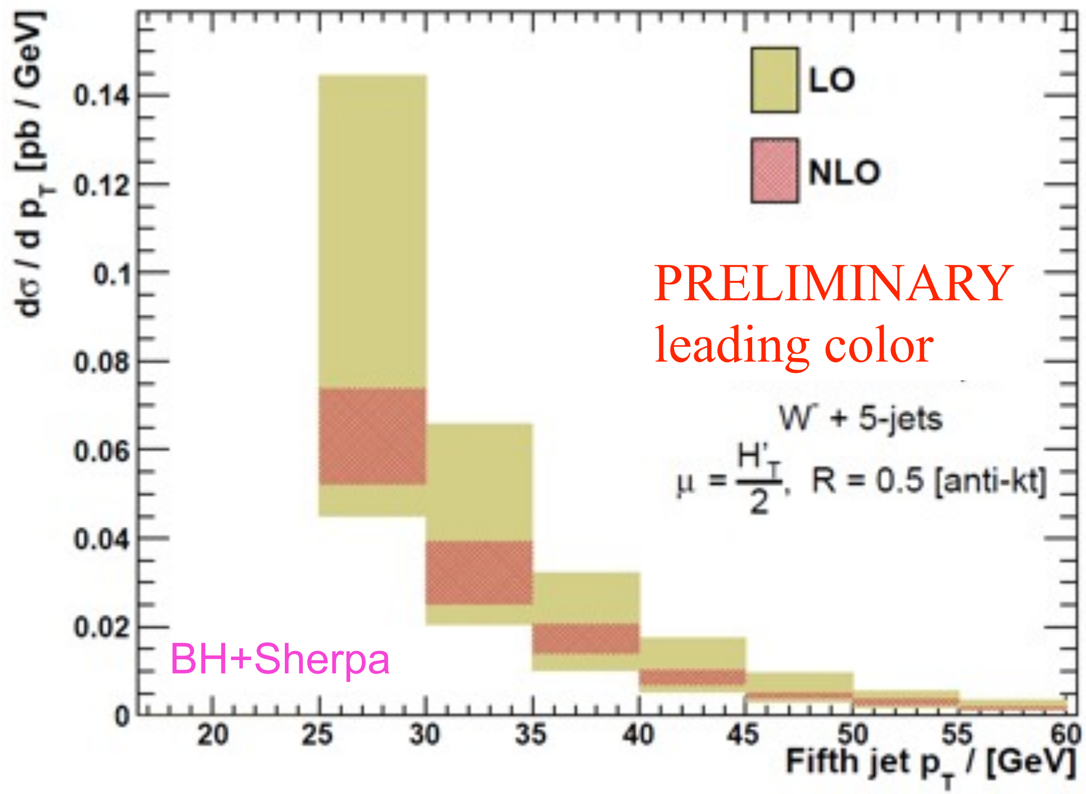


256,265 +

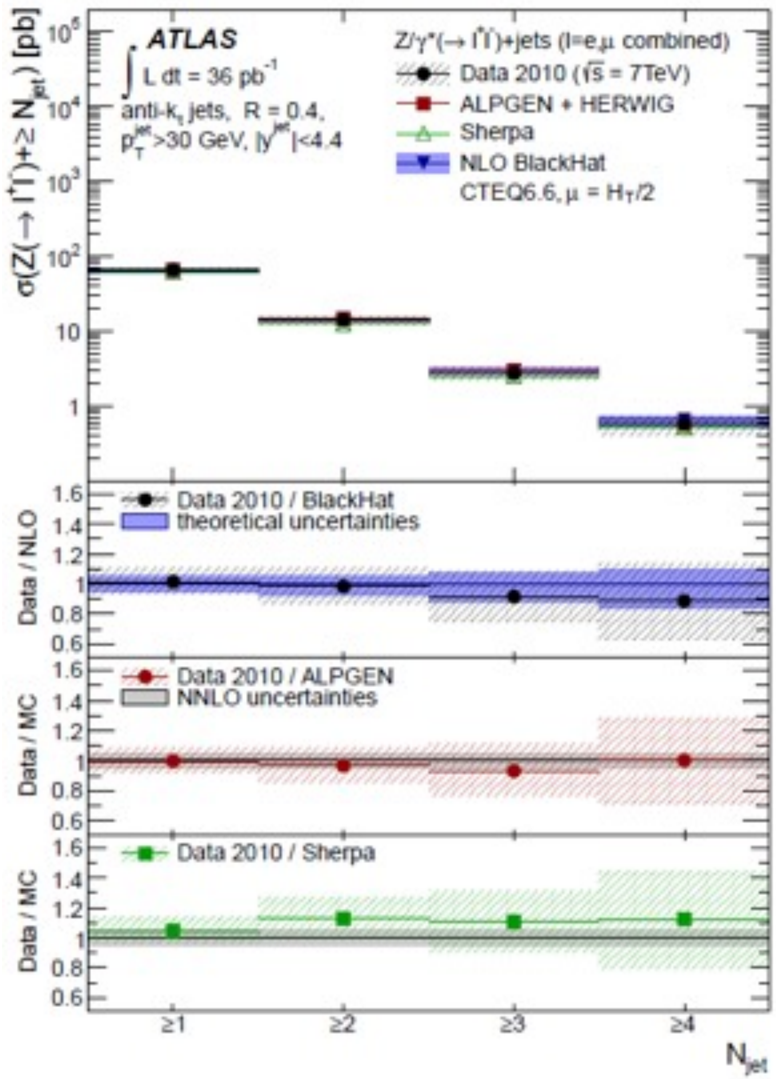


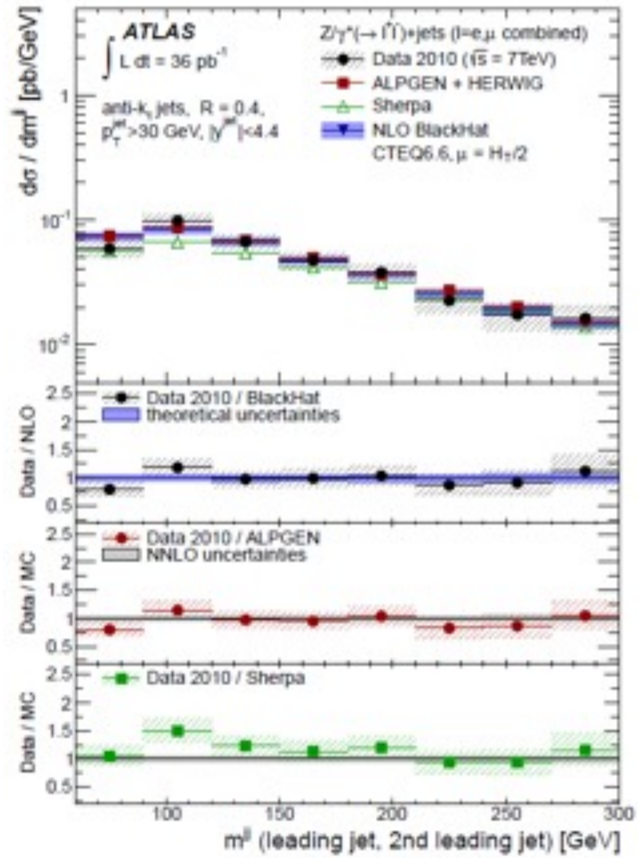
49,614 + …

Brand New!



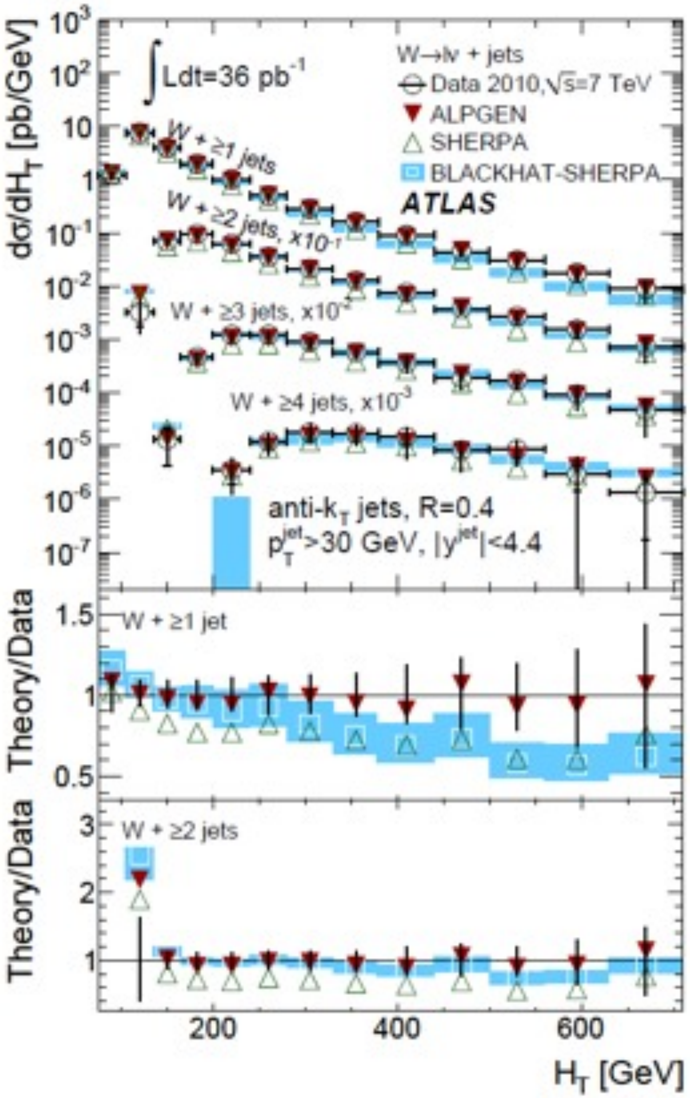
NLO $pp \rightarrow Z + 1,2,3,4$ jets vs. ATLAS 2010 data

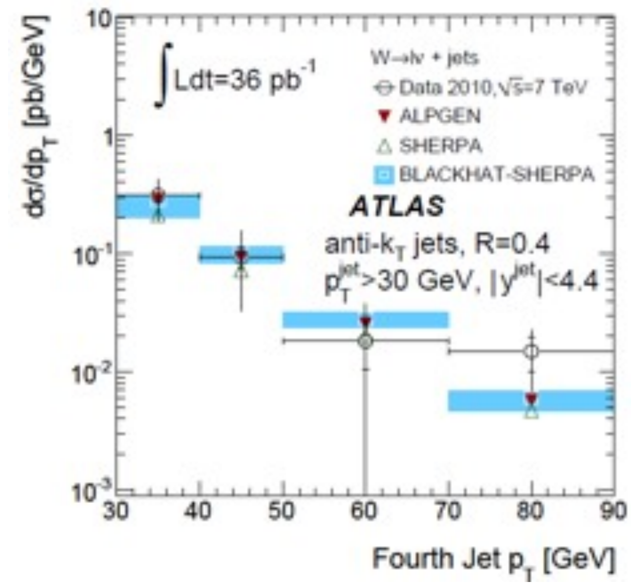




Analysis in progress with
full 2011 data set:
> 100 times the 2010 data

NLO $pp \to W + 1,2,3,4$ jets vs. ATLAS 2010 data

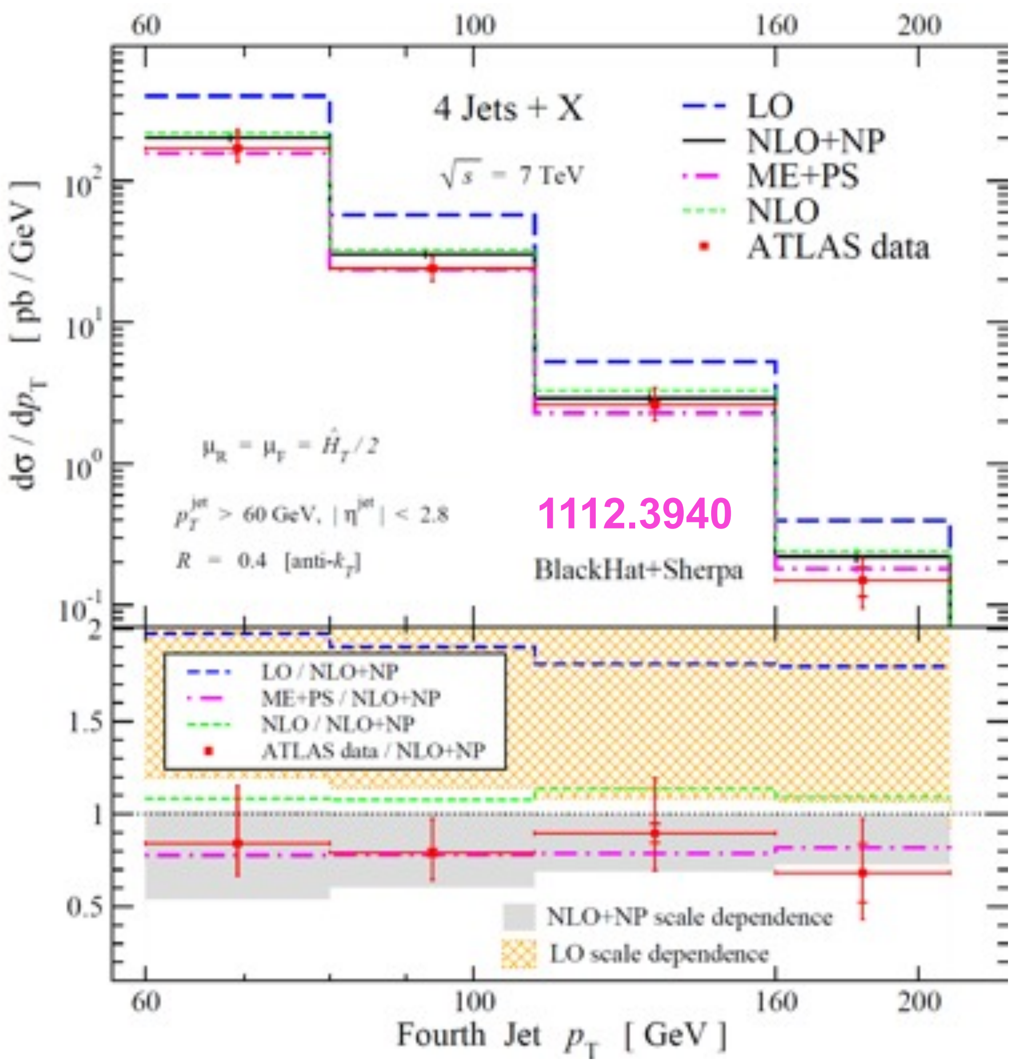




NLO undershoots badly for W + 1 jet – production dominated by W + 2 parton configurations. Theory can be improved here: Rubin, Salam, Sapeta 1006.2144

Analysis in progress with full 2011 data set: > 100 times the 2010 data

Pure QCD: *pp* → 4 jets vs. ATLAS data



4 jet events might hide pair production of dijet-decaying colored particles

Detailed study of multi-jet QCD dynamics may help understand other channels

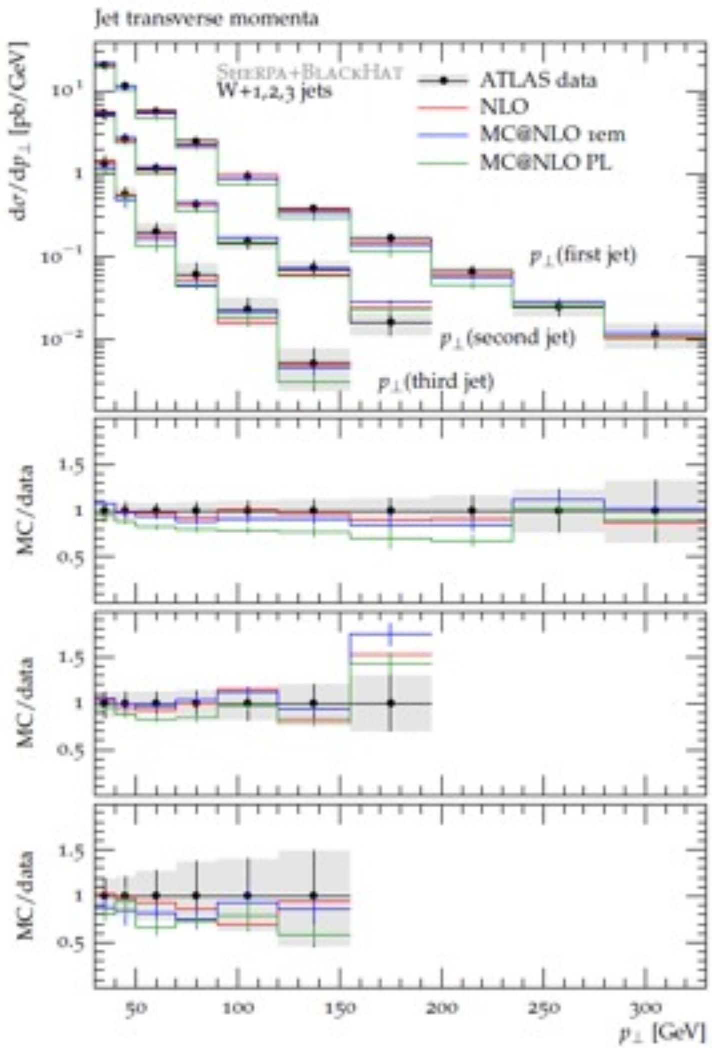
Fixed order vs. MC

- Last few plots NLO but fixed-order, parton level: no parton shower, no hadronization, no underlying event (except as estimated as corrections).
- Methods available for matching NLO parton-level results to parton showers, with NLO accuracy:
  - **MC@NLO** Frixione, Webber (2002) + SHERPA implementation
  - **POWHEG** Nason (2004); Frixione, Nason, Oleari (2007)
  - **GenEvA** Bauer, Tackmann, Thaler (2008)
- Recently implemented for increasingly complex final states

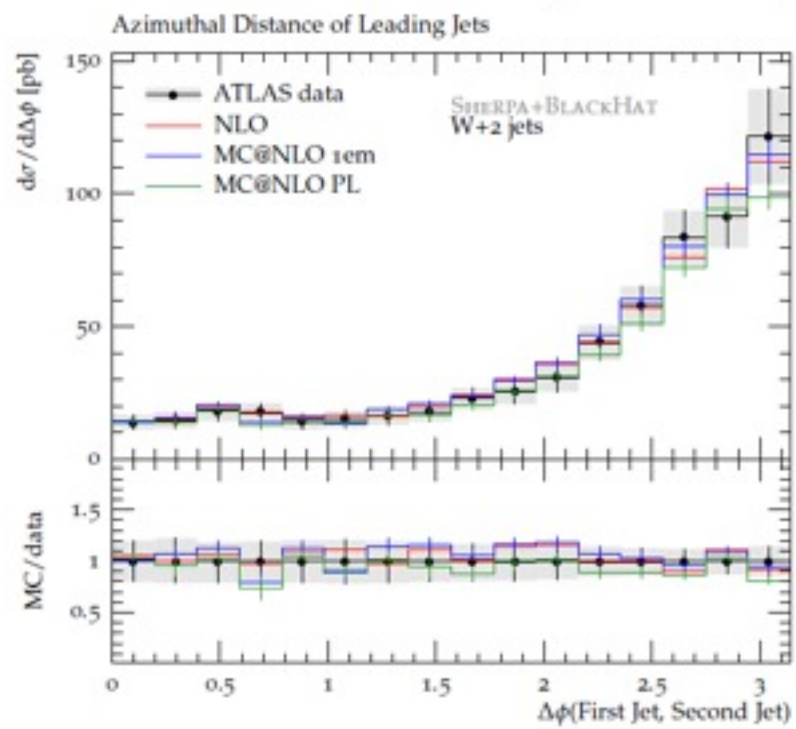
Remarkable NLO+MC progress

- Some recent NLO+shower processes:
  - 2 jets — Alioli, Hamilton Nason, Oleari, Re, 1012.3380 [POWHEG]
  - Z + 1 jet — Alioli, Nason, Oleari, Re, 1009.5594 [POWHEG]
  - W + b $\bar{b}$ — Oleari, Reina, 1105.4488 [POWHEG]
    Frederix et al., 1106.6019 [aMC@NLO]
  - W^+W^+ + 2 jets — Jäger, Zanderighi 1108.0864 [POWHEG]
  - W + 2 jets — Frederix et al., 1110.5502 [aMC@NLO]
  - $t\bar{t}$ + 1 jet — Alioli, Moch, Uwer, 1110.5251 [POWHEG]
  - $t\bar{t}$ Z — Garzelli, Kardos, Papadopolous, Trócsányi et al., 1111.1444
  - W + 3 jets — Höche, Krauss, Schönherr, Siegert, 1201.5882 [SHERPA]

NLO MC for W + 1,2,3 jets vs. ATLAS data



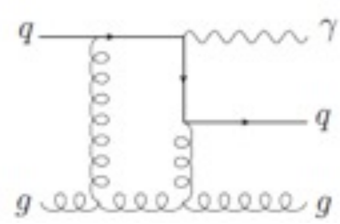
Höche et al., 1201.5882

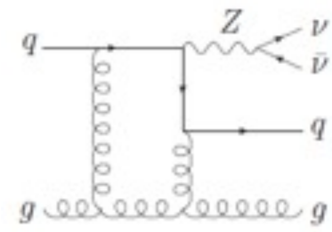


Ratios and data-driven methods

- Experimentalists don't entirely trust NLO theory for background estimates – even if NLO+MC is available. (Nor should they…)
- Data-driven methods use measurement of a control process, plus theory for a ratio
- Ratio usually computed using LO+shower simulations (ALPGEN/Pythia, MadGraph/Pythia, Sherpa, ...)
- Can improve using NLO [+MC] for ratios. The right ratios are considerably less sensitive to shower and nonperturbative effects.
- Some V + jets examples:
- [W + n jets]/[Z + n jets]
- [W^+ + n jets]/[W^- + n jets]
- [γ + n jets]/[Z + n jets]
- W polarization fractions
- [V + n jets]/[V + (n-1) jets]

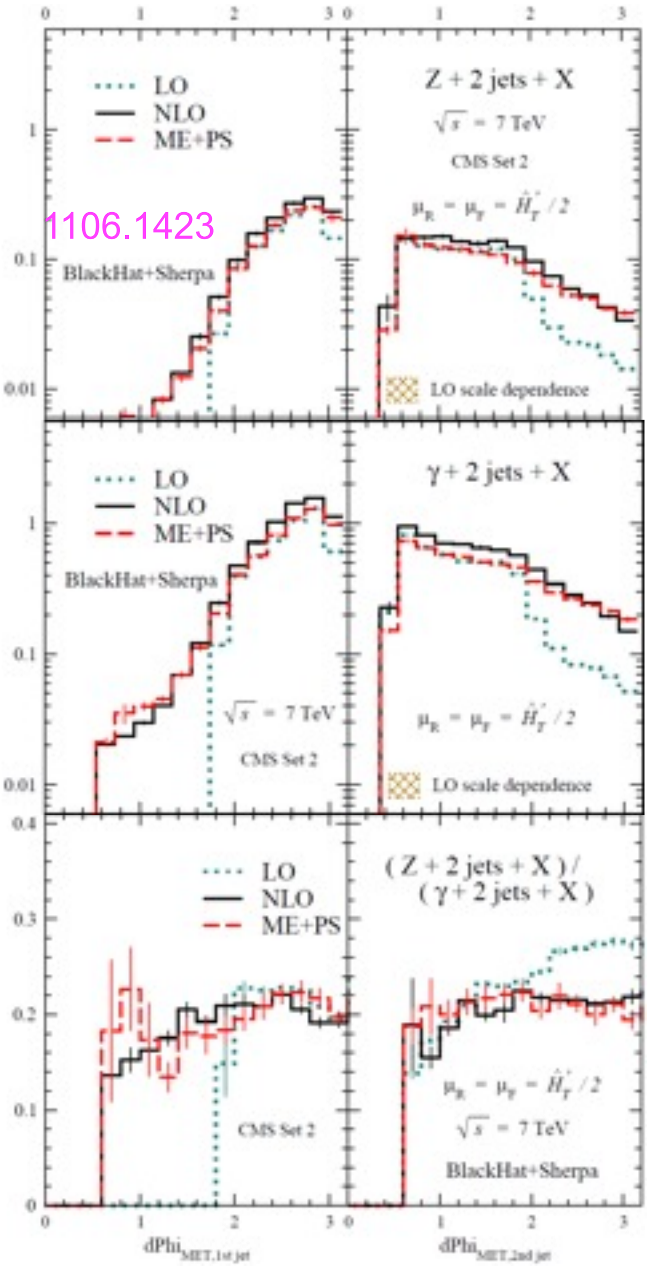
NLO (γ + 2 jets)/ (Z + 2 jets)





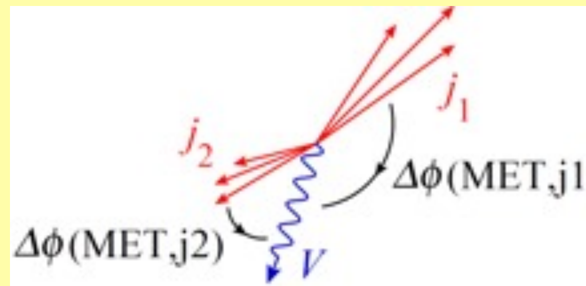
1106.1423

- CMS and ATLAS both use γ + jets to "calibrate" Z ($\rightarrow$ $\nu\nu$) + jets SUSY background.
- High rate compared to Z ($\rightarrow$ l^+l^-), relatively clean.
- How much does a γ behave like a Z?
- Photon-quark collinear pole is cut off by Z mass in the Z case. Does this make much difference?
- Assess by computing (γ + 2 jets)/ (Z + 2 jets) distributions in various kinematic variables, at LO (just for reference), NLO and LO+shower (ME+PS).



(γ + 2 jets)/(Z + 2 jets)

• Most difference seen in distribution in azimuthal angle in transverse plane, between vector boson (MET) vector and p_T vector of 1st and 2nd jets.



• LO way off – kinematics too restrictive. NLO and ME+PS agree to within about 10% in Z/γ ratio.

• Used by CMS to estimate uncertainty in Z (→ νν) + jets in SUSY search [1106.4503]

• Now studying for *V* + 3 jets, tighter cuts for full 2011 data.

Conclusions

- New and efficient ways to compute one-loop QCD amplitudes supplant Feynman diagrams for important Standard Model backgrounds at the LHC
  - exploit **analyticity/unitarity**: build loop amplitudes out of trees
  - implemented **numerically** in several programs: **BlackHat**, **CutTools, MadLoop, NGluon, Rocket, Samurai, …**
- Long and growing list of complex processes computed at NLO with these techniques
- Also very important to incorporate into NLO Monte Carlos, a la MC@NLO & POWHEG methods
- Good agreement with LHC measurements (so far)
- Ratios at NLO for data-driven methods
- Success assisting in optimal exploitation of LHC data

Cast of dozens

BlackHat, past and present:
Berger, Bern, Diana, LD, Febres Cordero, Forde, Gleisberg, Höche, Ita, Kosower, Maître, Ozeren

Other key contributors:
Anastasiou, Badger, Bevilacqua, Biedermann, Britto, Cachazo, Czakon, Dunbar, Ellis, Feng, Frederix, Frixione, Garzelli, Giele, Hirschi, Kardos, Kunszt, Maltoni, Mastrolia, Melnikov, Ossola, Papadopoulos, Pittau, Reiter, Schulze, Tramontano, Uwer, van Hameren, Weinzierl, Winter, Witten, Worek, Zanderighi, …